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Solar controls of fire events during the past 600,000 years

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ABSTRACT

Fires have accompanied terrestrial life from the beginning, yet with incomplete knowledge about feedback to paleoclimate and vegetation. Here, we have assessed how climate triggered the activity of vegetation fires in a 600,000 years continental record. We recorded benzene polycarboxylic acids as markers for burned organic carbon residues (BC) in sediments of Lake Van (Turkey), one of the oldest lacustrine archives currently available on Earth. Though fire and BC peaks were assumed to occur during dry climates, BC concentration and related fire temperatures were largest during periods of warm/humid climatic conditions. During humid periods, we recorded up to 45 mg BC per cm^3 sediment (precipitation ~ 800 mm/a), while BC amounts during dry climates were smaller by a factor of 10 (<5 mg BC per cm^3 sediment, precipitation < 200 mm/a). Overall, BC concentration in Lake Van sediments paralleled that in other lake sediments. They all following orbital forcing, showing that fires events peak globally with a cyclicity of ~100,000 years.

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1. Introduction

Vegetation fires and residues of incomplete combustion (black carbon, BC, see e.g., Andreae and Gelencsér (2006) for definitions) are relevant to climate: atmospheric BC has a direct effect on earth's energy budget as on the albedo (Crutzen and Andreae, 1990; Watson et al., 2005); in soils and sediments BC contributes to carbon (C) storage (Forbes et al., 2006; Preston and Schmidt, 2006).

The relationship between fire activity and climate is not always linear. In regions with a warm and dry summer climate, such as the Mediterranean area, high fire activity was correlated with drought events (annual precipitation < 200 mm) (López-Blanco et al., 2011; Bernhardt et al., 2012; Colombaroli and Tinner, 2013). Thonicke et al. (2010) argued that in regions with an annual precipitation of <250 mm, biomass production may be too low to sustain frequent burning events, as it is the case in extremely cold and extremely hot regions. Hallett and Anderson (2010) showed that fire intensity increased in mountainous regions with warmer summer temperatures as compared to colder summers. Similarly, an increase in grassland vegetation due to climate cooling might promote fires (Schatz et al., 2011; Wang et al., 2012). As humidity affects ignitability, and thus the frequency and intensity of fires (Marlon et al., 2013), Daniau et al. (2012) demonstrated that fires are most frequent at a medium level of humidity, fortified by elevated mean annual temperatures. In both, diachronic marine sediment records and in satellite remote-sensing records, the relationship between biomass burning and temperature was nearly linear, with biomass burning higher for ecosystems growing at intermediate level of moisture (Daniau et al., 2012, 2013; Marlon et al., 2013; Bistinas et al., 2014). Therefore, fires could have reacted to periodic changes in climate.

The Quaternary is characterised by periodic changes of cold/dry glacial and warm/wet interglacial climates with a main recurrence of ~100,000 years at least during the last ca. 700,000 years (Imbrie et al., 1993). Jouzel et al. (2007) reconstructed the climate and atmospheric history of the past 800,000 years from the EPICA Dome Concordia (EDC). Furthermore, Wolff et al. (2010) and Barker et al. (2011) synthesized the temperature of the past 600,000 years with the help of the Greenland ice-core record (NGRIP) and the modelled synthetic ice-core record $GL_{T\text{-}syn}$. They found that temperatures followed orbital forcing (precession, obliquity and eccentricity of the Earth's orbit), resulting in changes with a periodicity of about 100,000 years. For the Lake Van area, it was reported that changes in summer insolation correlated with major vegetation changes (Litt et al., 2014). However, to understand the systematic shifts in past ecosystems and fire regimes, and to evaluate the effects of

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drivers of climate change on fire ecology, much longer fire records are needed than those studied in terrestrial contexts so far (Marlon et al., 2013).

A complete series of lacustrine sediments was drilled in 2010 in Lake Van, Eastern Anatolia, Turkey (Litt et al., 2014). During the last ~600,000 years, the record shows a distinct vegetation change between desert-steppe vegetation (indicated by Chenopodiaceae, *Artemisia,* and *Ephedra*) and open oak steppe-forest (indicated by deciduous *Quercus*, *Pinus* and Poaceae) (Litt et al., 2014). The first connection of climate conditions and vegetation changes with fire intensity was investigated by microscopic charcoal counting for the last two interglacial-glacial cycles (between ~250 and 10 ka BP) (Pickarski et al., 2015a, 2015b; Pickarski and Litt, 2017). High charcoal amounts (>20 μm) correlated to high arboreal pollen (AP) values (Pickarski et al., 2015a, 2015b; Pickarski and Litt, 2017). However, as further charcoal investigations are missing for other time frames at Lake Van, and as this approach does not allow fire temperature reconstruction, we took advantage of a geochemical tracer approach that had been successfully applied to other lake sediment deposits (Lehndorff et al., 2015). The methodology relies on the oxidation of fire residues in sediments to benzene polycarboxylic acids (BPCAs) (Glaser et al., 1998; Brodowski et al., 2005; Kappenberg et al., 2016). The sum of BPCAs indicates changes in influx of black carbon, whereas the composition of BPCAs, i.e., the ratio of pentacarboxylic acid to mellitic acid (B5CA to B6CA), indicates changes in the general fire regime such as the fire temperature (Lehndorff et al., 2015; Schneider at al., 2013; Wolf et al., 2013).

The present study aims at i) identifying the relationships between fire residue input and its composition to changes in climate and vegetation, as well as, ii) finding hints to a global control of fire events. We hypothesized that fire activities are highest during dry periods and that the BC concentrations at Lake Van correlate with global patterns in vegetation, BC accrual and climate change.

1.1. Study area, regional and climate settings

Lake Van is located on the eastern Anatolian high plateau in a tectonically active area between the Afro-Arabian and the Eurasian Plates in Turkey (Fig. 1) (Kempe et al., 1991; Pickarski et al., 2015a; Reilinger et al., 2006). The lake has a volume of about 607 km^3 and a surface area of ca. 3570 km^3. Lake Van lies 1649 m above sea level (asl) and has a maximum water depth of about 460 m (Kempe et al., 1991; Kaden et al., 2010; Litt et al., 2012). Due to the east-west oriented mountains to the south (Bitlis Massif, Fig. 1), rainfall reaches up to 1200 mm per year at the southern slopes of the mountains, whereas precipitation in the north-east is usually lower than 430 mm/a (observation period: 1975–2008) (Litt et al., 2014). As a result of different rainfall amounts at Lake Van, the environment is characterised by two vegetation types: the Kurdo-Zagrosian oak steppe-forest and the Irano-Turanian steppe vegetation (Fig. 1) (Zohary, 1973; Frey and Kürschner, 1989; Litt et al., 2012).

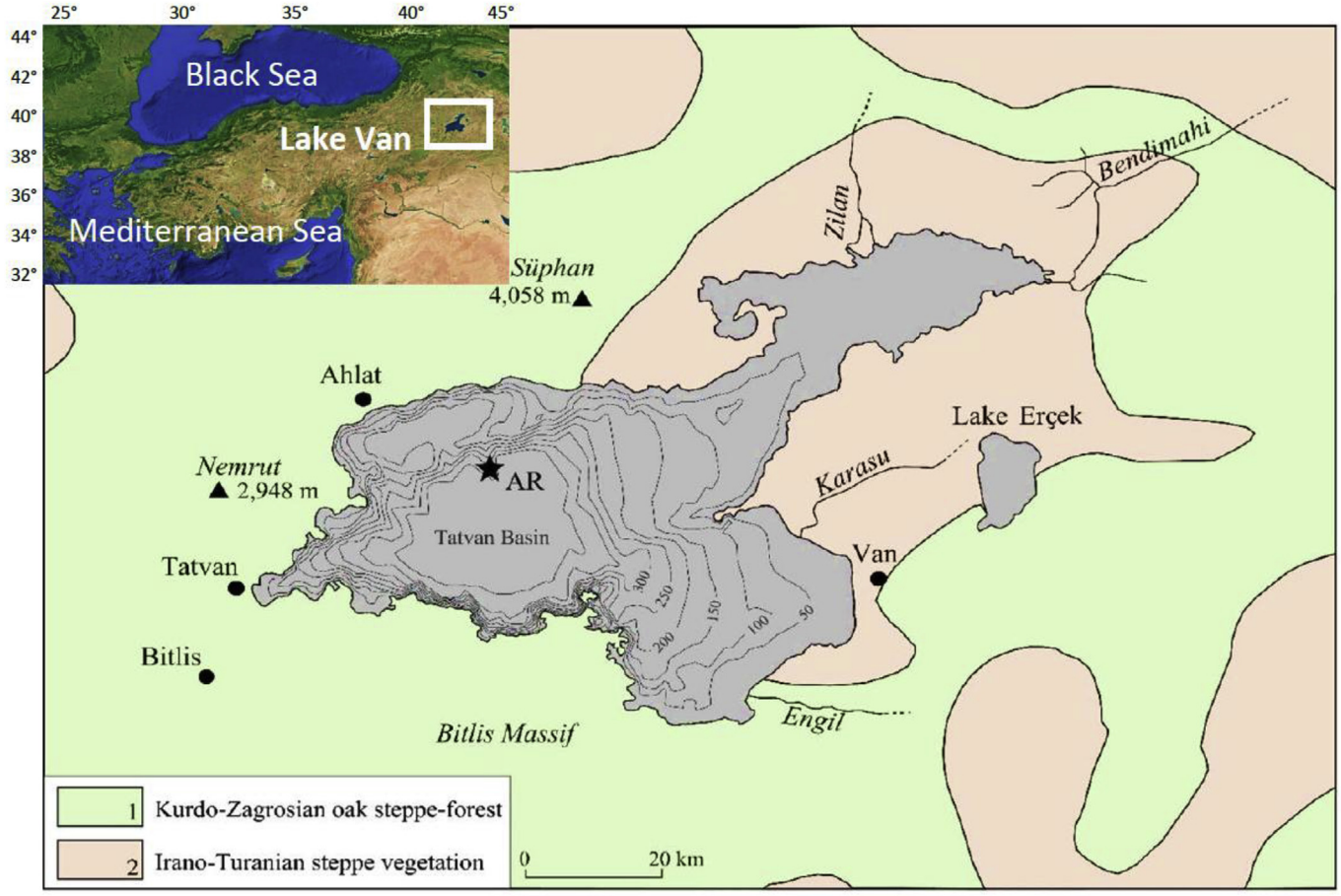

Fig. 1. a) Map of the eastern Mediterranean region with Lake Van. **b)** Bathymetric map of Lake Van (Kaden et al., 2010; Pickarski et al., 2015b) with two main vegetation types simplified after Frey and Kürschner (1989); (1) Kurdo-Zagrosian oak steppe-forest; (2) Irano-Turanian steppe vegetation (black star: Ahlat Ridge core (AR); black triangle: volcanoes Nemrut and Süphan; black dots: major cities, and rivers).

The continental setting at Lake Van has been strongly affected by tropospheric jet streams, subtropical high pressure, and the dry continental air masses of NE-Europe and Asia (Reiter, 1975; Roberts and Wright, 1993; Litt et al., 2012, 2014). During summers, subtropical high pressure has been leading to dry and hot summers in this region, whereas the subtropical jet and the Siberian high pressure has promoted cold and wet winters (Reiter, 1975; Akçar and Schlüchter, 2005; Stockhecke et al., 2014a, b).

The current climatic conditions, however, have not been stable in the Quaternary. During the last 600,000 years, the Lake Van pollen record documents several interglacial-glacial stages and pronounced interstadials (Litt et al., 2014). In general, the glacial/stadial vegetation at Lake Van is characterised by dwarf-shrub steppe and desert steppe, whereas the climax vegetation of past warmer interglacials (Marine Isotope Stages (MIS) 5e, 7, 9 11, 13 and 15) can be described as oak steppe-forest similar to the present interglacial (MIS 1) in this sensitive semi-arid region between the Black Sea, the Caspian Sea, and the Mediterranean Sea (Litt et al., 2014).

2. Material and methods

2.1. Sampling collection

The Ahlat Ridge (AR) sediment core (38°667′N, 42°669′E, Fig. 1), a 219-m composite below lake floor (mcblf) long sedimentary record, was recovered of seven parallel cores by the PALEOVAN scientific team. The cores were drilled during the International Continental Scientific Drilling Program (ICDP) in summer 2010 in about 357 m water depth (Litt et al., 2012). Detailed information regarding the construction of the composite profile, the age-depth model and sedimentological analyses can be found in Stockhecke et al. (2014a,b). For our study, 186 samples (at distance of 1 m, sample size of 1 cm^3) were analysed for BC through the entire length of the 219 mcblf core.

2.2. BC analysis

BC was assessed in all samples, using benzene polycarboxylic acids as molecular markers (Glaser et al., 1998), and following the revised protocol of Brodowski et al. (2005). Furthermore, the threshold of 5 mg organic carbon concentration per sample was strictly maintained, and BC quantification was restricted to BPCAs with five to six carboxyl groups (benzene pentacarboxylic acid and mellitic acid, B5CA/B6CA) (Kappenberg et al., 2016). Samples were analysed with a Hewlett Packard 6890 gas chromatograph (Hewlett Packard GmbH, Waldbronn, Germany) equipped with a flame ionisation detector and a HP-5 capillary column (30 m × 0.32 mm i.d., 0.25 μm film thickness, Macherey-Nagel, Düren, Germany; for oven program see Brodowski et al. (2005). Deviation from duplicate analysis was <5% and recovery of the internal standard (citric acid) was always > 79%. To convert BPCA to BC, Glaser et al. (1998) suggested to use a conversion factor of 2.27. It should be noted, though, that originally this factor was based on all BPCAs detected, while here we only used B5CA and B6CA for BC estimation to avoid potential biological origin or artefact formation (Kappenberg et al., 2016). Nevertheless, we decided to stick to the original conversion factor, because i) Glaser et al. (1998) reported a similar factor also for soils where B3CA and B4CA was lacking, and ii) in order to follow the recommendation of Brodowski et al. (2005) to use the conversion only as a sound, minimum estimate of BC contents.

3. Results

According to Litt et al. (2014), the Lake Van pollen record can be divided into 11 pollen assemblage superzones (PAS) based on changes in arboreal pollen (AP) percentages and changes in the relative frequency of individual taxa. Here, the broad correspondence warm/wet climatic intervals, respective periods of low global ice volume as defined by Marine Isotope Stages (MIS) (Lisiecki and Raymo , 2005) and terrestrial forest intervals based on long pollen records has been appreciated (Litt et al., 2014) (Fig. 2).

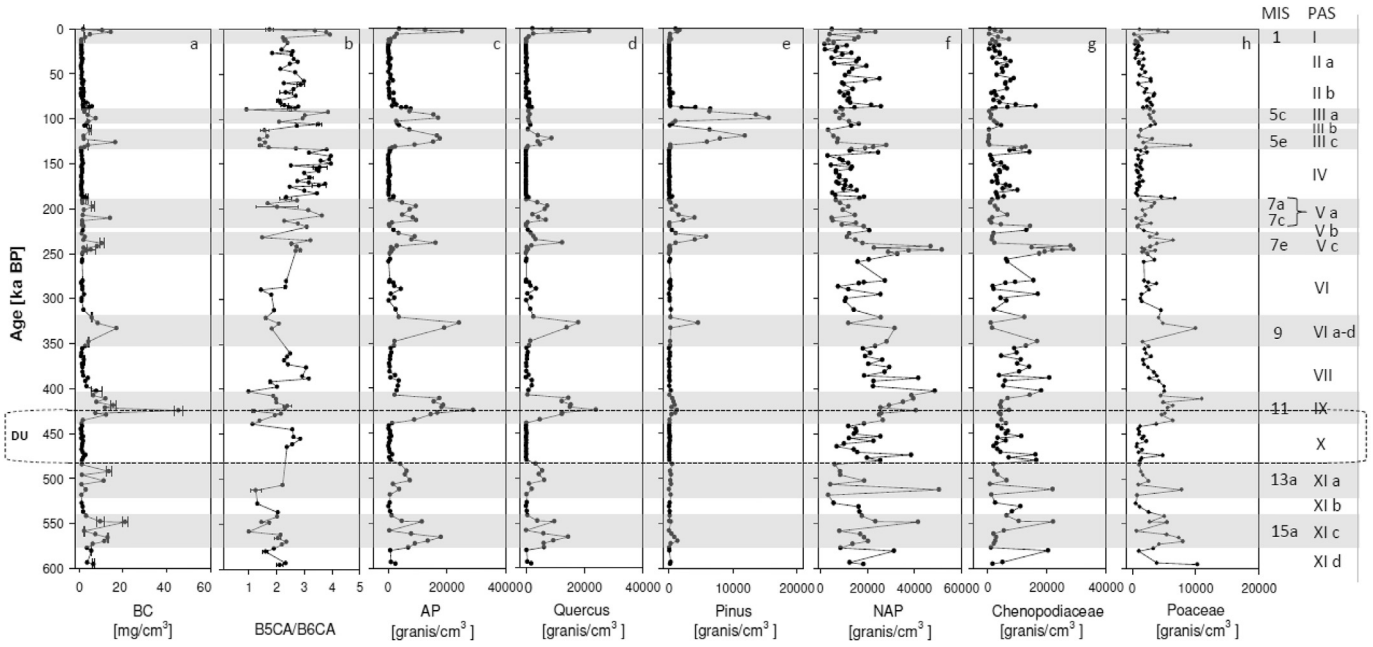

Fig. 2. **a)** Black carbon (BC) in mg per cm^3 and **b)** pentacarboxylic acid to mellitic acid (B5CA to B6CA) ratio in comparison to c) arboreal pollen (AP), **d)** deciduous *Quercus*, **e)** *Pinus*, **f)** non-arboreal pollen (NAP), **g)** Chenopodiaceae, and **h)** Poaceae pollen (in grain per cm^3) against Lake Van time scale constructed by Stockhecke et al. (2016). Furthermore, the different warm marine isotope stages (MIS; after Lisiecki and Raymo (2005) in grey and the pollen assemblage superzones (PAS) after Litt et al. (2014) are displayed. The Deformed Unit (DU) is indicated with dotted lines (no time control; see Stockhecke et al. (2016) for further details).

BC concentration [mg per cm^3 sediment] generally followed changes in micro-charcoal counts, but revealed more clearly peaking fire events (Fig. 3), e.g. BC analyses clearly showed a peak during MIS 5a (85–77 ka), which was not indicated by charcoal counting nor pollen analyses Furthermore, there are non-ignorable differences between the results of charcoal counting and BC analyses, e.g. during 0–10 and 80–90 ka BP. The gap between charcoal counts and BC analysis via BPCAs is likely a result of underestimation of fire residue influxes by charcoal counting, as soot and other submicroscale fire residues may escape this methodological approach (Clark and Patterson, 1997; Kaal et al., 2008).

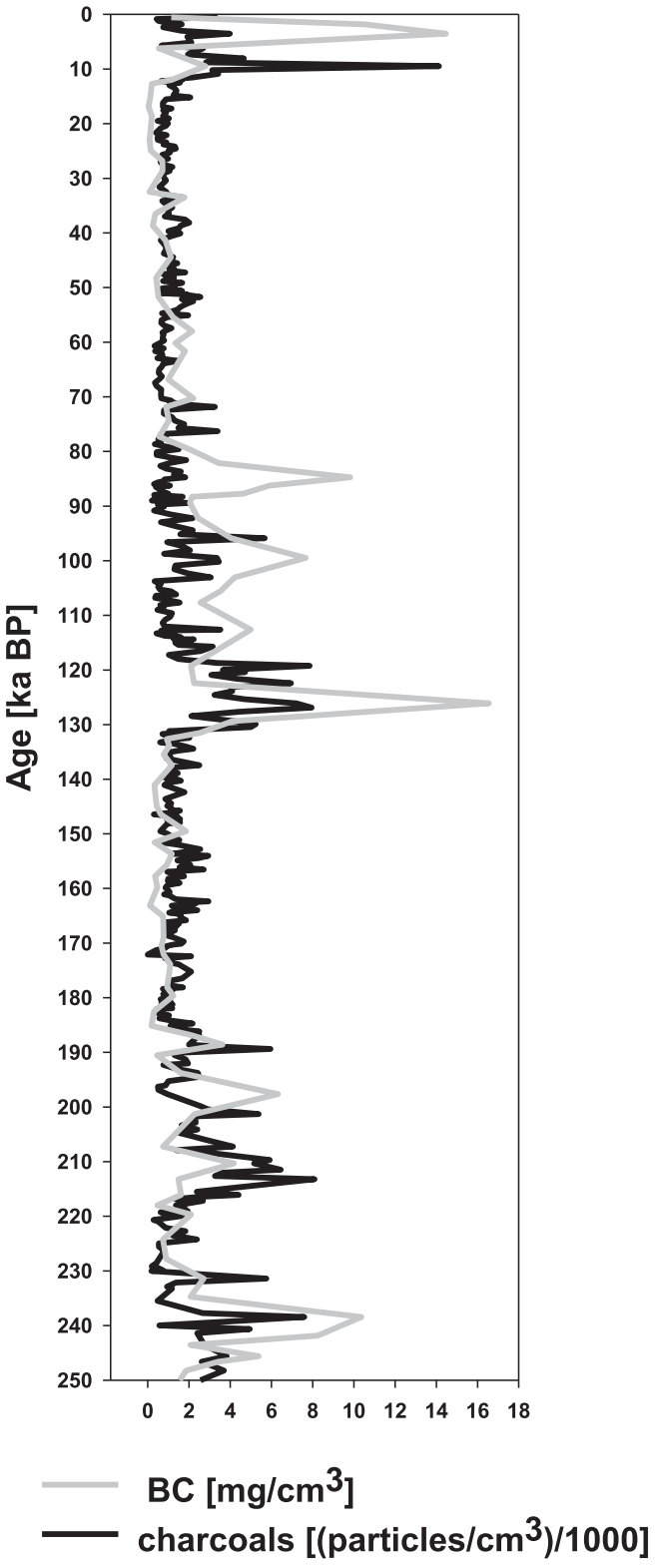

Fig. 3. Comparison of BC concentration with the concentration of micro-charcoal particles (>20 μm) (Pickarski et al., 2015a, b; Pickarski and Litt, 2017) in Lake Van.

The BC concentration changed among PAS, however, to different degrees (Fig. 2). The BC amounts during the PAS IIa, IIb, IV, VI, and VII, X were comparatively low (Fig. 2). These PAS are characterised as dry/cold steppe and/or desert steppe vegetation (Litt et al., 2014). Dry climates in lower elevation areas, as well as cold climates in mountain areas around Lake Van, restricted the growth of trees during these glacial periods (Litt et al., 2014). Such conditions did thus not coincide with frequent burning events.

We found BC peaks in the PAS I, IIIa, IIIc, Va, Vc, VIa-d, IX, Xia, and XIc (Fig. 2). All these PAS occurred during warm and comparatively wet climates (Litt et al., 2014) with growth of trees which also related to warm and comparatively wet climates (mainly deciduous *Quercus* and *Pinus*, Litt et al., 2014, Fig. 2). Overall, BC (Fig. 2) correlated significantly to AP concentration ($R^2 = 0.56$; $p < 0.001$), especially to that of thermophilous trees such as deciduous *Quercus* ($R^2 = 0.62$; $p < 0.001$). The correlation between BC and deciduous *Quercus* at the PAS I, VIa-d, IX, Xia, and XIc (MIS 1, 9, 11, 13, and 15) yielded a coefficient of determination of $R^2 = 0.7$ ($p < 0.001$). In these PAS, high BC amounts thus coincided with deciduous *Quercus* pollen (Fig. 2). The largest deciduous *Quercus* concentration in MIS 11 exhibited the best correlation to BC ($R^2 = 0.74$; $p < 0.001$) and accorded with maximum BC amounts (45.3 mg per cm^3 sediment) (Fig. 2). During MIS 5 and 7, the largest *Pinus* concentration of the record correlated less to BC ($R^2 = 0.4$; $p < 0.001$) than to the PAS with deciduous *Quercus* as the main vegetation type ($R^2 = 0.7$; $p < 0.001$). During glacial stages, a correlation between Chenopodiaceae (an indicator for dry/cold treeless steppe or semi desert-steppe vegetation) and BC contents could not be detected (Fig. 2; $R^2 = 0.02$). However, there was a correlation between the contents of BC and Poaceae pollen, which indicated a comparatively more humid forest steppe climate and less arid steppe climate, at the beginning of each warm stage (Litt et al., 2014; $R^2 = 0.4$; $p < 0.001$). The correlation was significant during the PAS I, VIa-d, IX, Xia, and XIc (MIS 1, 9, 11, 13 and 15) ($R^2 = 0.42$; $p < 0.001$). The sum of deciduous *Quercus, Pinus*, and Poaceae pollen to BC concentration yielded a significant correlation of $R^2 = 0.65$ and $p < 0.001$ throughout the complete sediment record.

The ratio of B5CA/B6CA related inversely to combustion temperature of charcoal (Schneider et al., 2013). We found the lowest B5CA/B6CA ratios in the *Pinus-Quercus* PAS IIIa (MIS 5c, ratio ~0.93) and in the *Quercus* PAS IX (MIS 11) stage (ratio ~1). In general, we found lower ratios of B5CA/B6CA in the warm stages and higher ratios in the colder stages (R^2=0.52; $p < 0.05$, MIS1 excluded; Fig. 2).

4. Discussion

At Lake Van BC concentration and fire combustion temperatures changed between comparatively cold and warm phases with vegetation composition (Litt et al., 2014; Fig. 2). Maximum BC concentration and elevated fire temperatures correlated predominantly with the abundance of deciduous *Quercus* and Poaceae in warm, and comparatively humid steppe-forest (Litt et al., 2014, Fig. 2). It has to be mentioned that deciduous *Quercus* trees were only thinly distributed, with large portions of productive understorey vegetation (Poaceae). During dry summers, indicating by high June insolation (Berger, 1978; Berger et al., 2007; Litt et al., 2014, Fig. 2), this steppe-forest environment thus offered an increased likelihood of hot fires. Fires were most likely fuelled by

dead dry wood, such as twigs, which then produced charcoal with low B5CA/B6CA ratios (Wolf et al., 2013) (Fig. 2). However, the abundance of oak co-appeared with maximum BC concentration in the lake sediment may not only be linked to higher productivity but also indicate additional controls of, e.g., precipitation, as also suggested by Daniau et al. (2012), Daniau et al. (2013), Marlon et al. (2013), and Bistina et al. (2014). This warm and comparatively humid climate promoted larger biomass production and thus the accrual of BC, while periods with cold and dry desert steppe and low biomass production led to low BC production, as also showed by Turner et al. (2008, 2010) and by Wick et al. (2003) for the last ~20 ka.

To obtain a better quantitative understanding of the conditions of paleo fire variations and related BC accumulation, we compared our findings with the modelled precipitation changes published in Stockhecke et al. (2016) (Fig. S1). We assume that in addition to above-mentioned vegetation controls, BC production was affected by precipitation and differences in the availability of dry fuels. For example, decreasing humidity may increase ignitability (Thonicke et al., 2010; Daniau et al., 2012, 2013; Marlon et al., 2013; Bistinas et al., 2014), another prerequisite for BC production. However, during dry glacials, BC concentration in Lake Van sediments was comparatively small (<5 mg BC per cm^3 sediment) (~200 mm precipitation/a) (Stockhecke et al., 2016). Stockhecke et al. (2016) also denoted MIS 2, 4, 6, and 8 as drought event stages (precipitation ≤ 100 mm/a), where we found the lowest BC amounts (<2 mg BC per cm^3 sediment). Under dry conditions, there was thus simply not enough biomass present to produce elevated contents of BC (Thonicke et al., 2010).

During warm and dry steppe-forest phases dominated by *Pinus* (e.g., MIS 5c), fire temperatures were highest (Fig. 2b) and likely also fire frequencies. But relatively low precipitation (~300 mm/a) probably led to a frequent reburning of BC (Czimczik and Masiello, 2007), resulting in only medium BC concentrations (5–7 mg BC per cm^3 sediment).

During the comparatively warm and humid oak steppe-forest period (maximum precipitation values up to 1200 mm/a) (Stockhecke et al., 2016) high seasonality occurred, with high precipitation in autumn, spring and winter and dry summers (Litt et al., 2014; Stockhecke et al., 2016). Here, high elevated biomass productivity in wet spring, burning in summer, and protection from reburning in wet autumn, and winter and dry summer led to the largest BC amounts in Lake Van (>10 mg BC per cm^3 sediment). This agrees with other studies reporting that highest fire activities are linked to medium moisture (Daniau et al., 2012; Marlon et al., 2013) and spring insolation (Inoue et al., 2018). Furthermore, Turner et al.

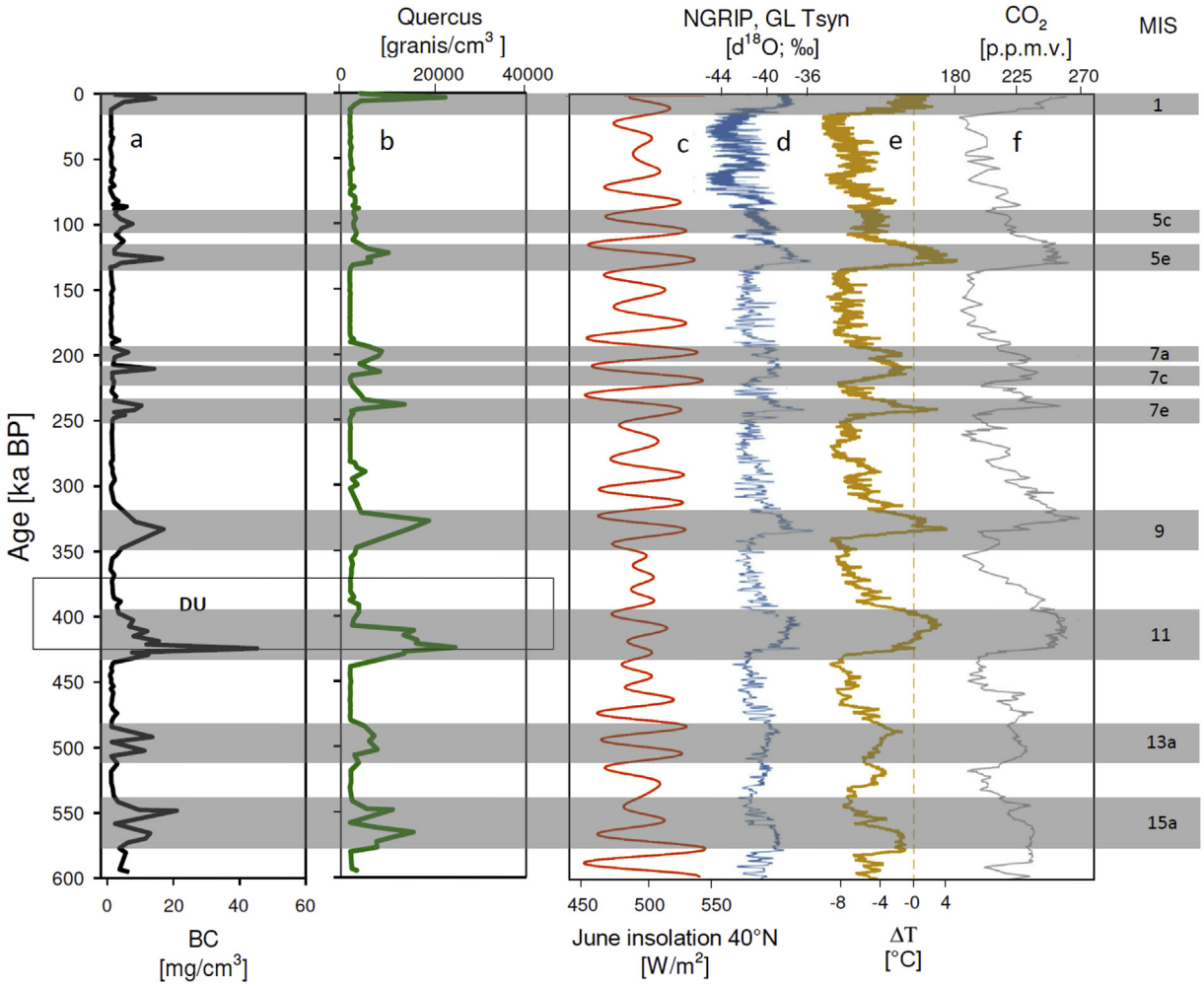

Fig. 4. **a)** Black carbon (BC) in mg per cm^3 and **b)** deciduous *Quercus* pollen in grains per cm^3 of the past 600,000 years at Lake Van from Litt et al. (2014), **c)** Mid-June insolation 40°N (W/m^2) after Berger (1978), data available as supporting material in Berger et al. (2007), **d)** Greenland ice-core record NGRIP (Wolff et al. (2010) and synthetic ice-core record $GL_{T\text{-}syn}$ (Barker et al., 2011), **e)** Isotopic temperature of atmosphere, and **f)** CO_2 concentration in parts per million volume (p.p.m.v.) after Jouzel et al. (2007). The grey bars document the different warm marine isotope stages (MIS; after Lisiecki and Raymo (2005). The Deformed Unit (DU) is indicated in black box (no time control) (Stockhecke et al., 2016).

(2008, 2010) and by Wick et al. (2003) also demonstrated for inner Anatolia that fire events occurred during wet climatic periods due to an increase in the vegetation biomass during the past about 20 ka. years. In addition, there is likely a positive feedback loop between higher biomass contents at more humid conditions and thus finally larger amounts of BC produced, as already outlined by Glaser and Amelung (2003).

The occurrence of six interglacial-glacial cycles at Lake Van uniquely allows the investigation of how natural fires correlate to climate change parameters (CO_2, temperature, and insolation). As it is generally accepted that changes in global climate followed the Milankovitch cycles, e.g. the slow changes in the tilt of the Earth's axis (precession) and shape and change of its orbit (eccentricity), it seemed reasonable to assume that such events also affected fire cyclicity. This orbital forcing induced large interglacial-glacial changes, enhanced atmospheric CO_2 concentrations, and elevated temperatures around 570, 470, 410, 320, 240, and around 130 ka years BP (Fig. 4). BC concentration at Lake Van followed the curve tendency as recorded for temperatures, CO_2 and $\delta^{18}O_{atm.}$ values for the past 600,000 years from the EDC ice core record, Antarctica (Jouzel et al., 2007), as well as from the Greenland ice-core, NGRIP (Wolff et al., 2010) in combination with the modelled synthetic ice-core record $GL_{T\text{-}syn}$ (Barker et al., 2011). Peaking BC concentration was thus found in time frames with high June insolation amounts >500 W/m^2 (Berger, 1978; Berger et al., 2007), which appeared roughly every 100,000 years, exhibiting double peak of the MIS 5 and MIS 7 interglacial-interstadial complexes (Fig. 4). This indicates that fire cyclicity is largely controlled by orbital forcing, particularly by the cycles of eccentricity.

We found that biomass productivity, precipitation and seasonality were major controls of fire activity, fire temperature and thus of the abundance and properties of BC. Findings showed that fire residue input was not mainly promoted by dry grass-steppe climates, as formerly assumed by, e.g., Pyne et al. (1996), Schatz et al. (2011), Wang et al. (2012), and, but contrarily during humid periods as suggested by Daniau et al. (2012, 2013), Marlon et al. (2013) and Bistina et al. (2014). In the terrestrial archive of Lake Van it were mainly dry summers, indicating by high June insolation (Berger, 1978; Berger et al., 2007; Litt et al., 2014, Fig. 2), during humid periods that promoted hot burning events of the understorey

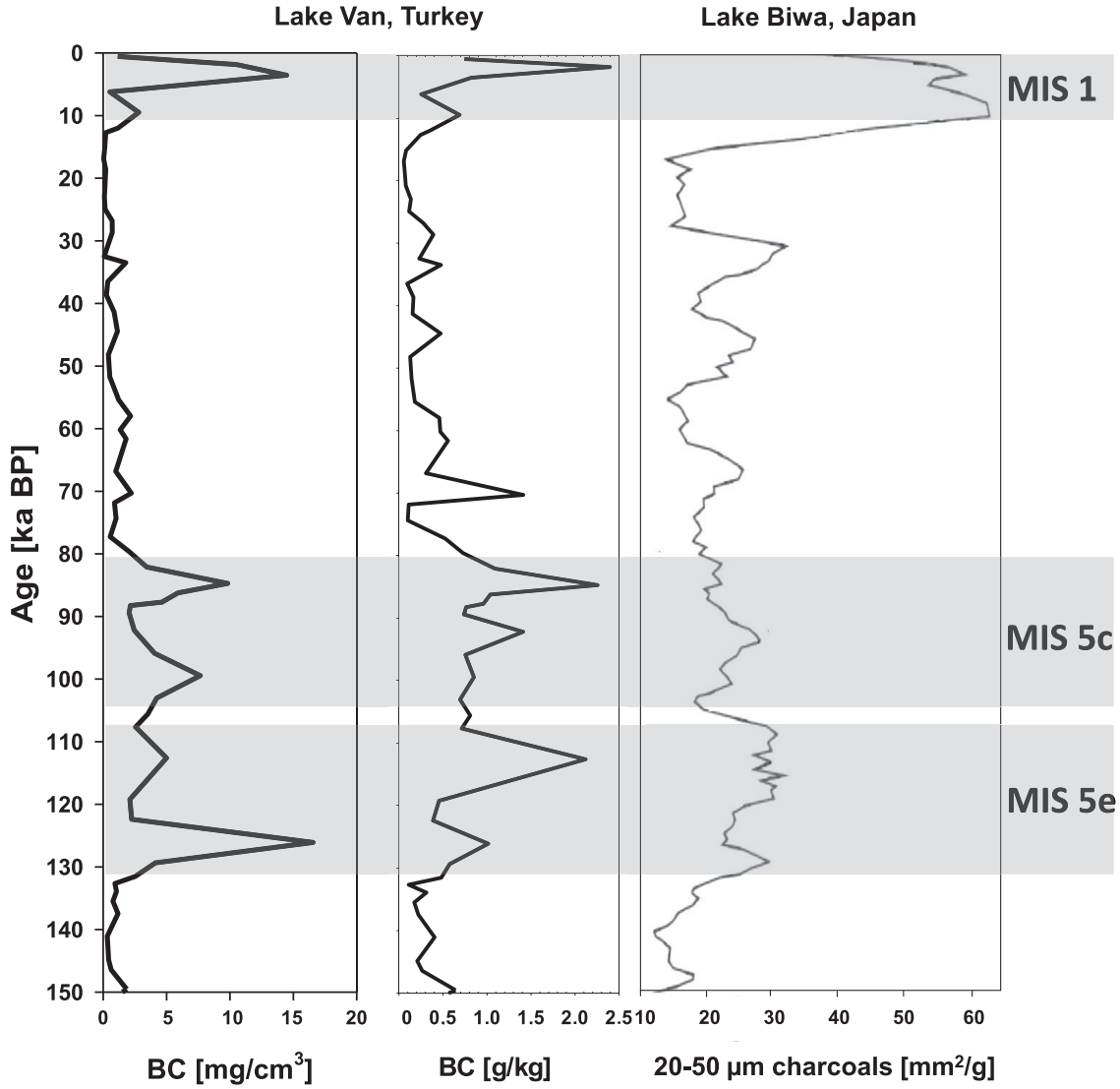

Fig. 5. Charcoal contents from Lake Biwa (Japan) (Inoue et al., 2018) compared to BC record from Lake Van Peaks in fire intensity are coloured in grey.

vegetation rather than prolonged dry periods with overall sparse vegetation that drove the BC cycle. When climate conditions repeated, also the accumulation patterns of BC repeated, thus revealing a cyclicity of fire in the last 600,000 years.

4.1. Global comparison

We are not aware of other continuous terrestrial archives analysed for fire residues that are older than 150,000 years, and which could elucidate the role of orbital forcing by e.g. Milankovitch cycles on burning events for the 600,000 years period archived in Lake Van. However, a comparison of our results with a 15,000 years lake sediment record from Germany (Lehndorff et al., 2015) revealed coinciding BC peaks during MIS 1. This is a first hint towards a global control of fire activities, indicating that fire activity increased also in other climate zones.

For other regions only charcoals records exist, which are only partly comparable to BC records. In contrast to charcoals BC covers a more complete spectrum of fire residues, e.g. the visible and the non-visible part, including aerosols, which can be transported via the atmosphere for over several 1000 of kilometres.

However, Inoue et al. (2018) analysed a charcoal size class in Lake Biwa in Japan (Fig. 5) which is also transportable in the atmosphere (20–50 μm). They found that fires peaked during warm periods in MIS 1, 5e, 7a, 7c, and 7e. Although they found further charcoal inputs during warm periods in MIS 3, this suggests gross links of fire to global climate change within the last 150,000 years (Fig. 5). Hence, increasing fire activities recorded for warm periods MIS 7, 9, 11, and 13 in Lake Van can also be interpreted as a result of global climate control on fire.

At least two marine studies exist reporting charcoal data going back to 200,000 and 1 million years (as elemental carbon; Atlantic Ocean, west of Sub-Sahara) (Verardo and Ruddimann, 1996; Bird and Cali, 1998). Contrary to the terrestrial sediment records, they reported that fire residue input peaked in glacial times, however, already questioning whether marine records are disturbed by changes in wind directions, strength, and allocation of source regions.

5. Conclusion

We here found strong evidence that fire intensity and fire temperature of the past 600,000 years were largest during periods of warm/humid climatic conditions, corresponding to the periods when forests-steppe were most abundant. Periodic changes in fire activity of Lake Van followed climate change, hence are related globally to orbital forcing, respectively eccentricity, with a cyclicity of ~100,000 years.

Contributions

A.K., E.L. and W.A. wrote the main manuscript text. A.K. did lab work and prepared figures. T.L. and N.P. provided core material from Lake Van. A.K., E.L. and W.A. designed the study. All authors reviewed and edited the manuscript.

Competing financial interests

The authors declare no competing financial interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2019.02.008.

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